Photoemission Studies of Quantum Well States in Magnetic Heterostructures

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INTRODUCTION

Magnetic artificial nanostructures such as ultrathin films and multilayers exhibit fascinating behavior such as the giant magnetoresistance (GMR)[1] and the oscillatory magnetic coupling[2,3] that are important for applications in magnetic information storage. Since these new properties originate from the behavior of the electrons in the system, angle-resolved photoemission spectroscopy (ARPES) is an ideal tool to untangle the puzzle of how changes in the electronic structure lead to new magnetic properties. In layered systems, the reflection of electrons at the interfaces can lead to standing electron waves known as quantum well (QW) states[4] that are confined inside a particular layer (Fig. 1), similar to an optical Fabry-Perot interferometer. Unlike bulk states, these QW states occur only at particular energies. This is analogous to a guitar string, which can vibrate only at certain discrete frequencies. The great interest in these QW states arise from their *spin-polarized* character, which is believed to play an important role for the oscillatory magnetic coupling, GMR, magneto-optics, and other magnetic phenomena.

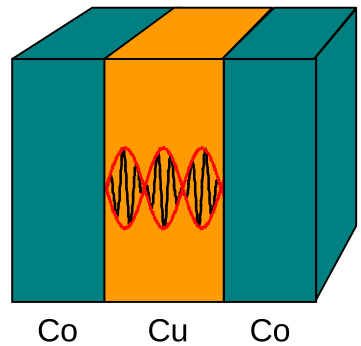

Figure 1. Quantum well states are standing electron waves that form due to reflections at the interfaces.

The results obtained in 1998 were (1) understanding of how the QW states lead to the oscillatory magnetic coupling,[5] and (2) directly probing the spatial variation of the QW wavefunction.[6]

SPECIAL CAPABILITIES OF THE ALS

These experiments were performed at beamline 7.0.1.2 to take advantage of the high photon intensity and small spot size (~50-100 microns). This enables the use of wedged samples for detailed thickness dependent studies of the QW states. By scanning the photon beam across a wedge or double-wedge, many independent measurements can be performed on a single sample. A typical scan over a double-wedge sample consists of ~2500 independent measurements corresponding to ~2500 different combinations of film thicknesses. Such capabilities are unparalleled and the experimental results obtained in 1998 demonstrate the new type of questions which can be investigated using third generation synchrotron sources.

PROJECT I: QW STATES AND THE OSCILLATORY MAGNETIC COUPLING

A ferromagnet/non-magnet/ferromagnet trilayer exhibits a magnetic coupling such that the magnetization of the two ferromagnetic (FM) layers will be either parallel or antiparallel, depending on the thickness of the non-magnetic layer. While this phenomena is present in many trilayer systems, the Co/Cu/Co(100) system has emerged as a model system because of the good epitaxial growth and simple Fermi surface of Cu. In 1992-1993, ARPES experiments on a Cu thin film on fcc Co(100) identified spin-polarized QW states forming inside the Cu layer.[4,7,8] Since the thickness dependence of the QW states seemed to match that of the oscillatory magnetic coupling, it was suggested that the QW states are responsible for generating the oscillatory magnetic coupling. In this work, ARPES was used to measure both the QW states and the magnetic coupling on the same sample (Fig. 2). This enabled a direct comparison of the electronic behavior (QW states) and the magnetic behavior (oscillatory coupling) for the first time.

The sample involved a Cu wedge grown on top of fcc Co(100).[9] Subsequently, a Co capping layer was deposited on half of the sample, as shown in Figure 2a. The magnetic coupling was measured on the side with the Co cap, and the QW states were measured on the side without the Co cap. In this manner, the Cu thickness on the two sides are exactly matched and a direct comparison is possible.

For the QW measurement, the density of states was measured (DOS) at the belly and neck of the Cu Fermi surface.[10] These points in momentum space correspond to the two extremal spanning vectors of the Cu Fermi surface for directions parallel to [100], and thus are believed to contribute most to the magnetic coupling in Co/Cu/Co(100). The DOS at the belly of the Fermi surface was measured with 83 eV photons and a normal emission geometry (Fig. 2b), and exhibits oscillations with a 5.6 ML periodicity of the Cu thickness. The DOS at the neck of the Fermi surface was measured with 77 eV photons and 11 degrees off-normal emission (Fig. 2c), and exhibits oscillations with a 2.7 ML periodicity of the Cu thickness.

For the magnetic coupling measurement, the magnetization direction of the top Co layer was measured by magnetic x-ray linear dichroism (MXLD)[11] in the Co 3p photoemission peak (Fig. 2d). The coupling exhibits two periods of oscillation (5.6 ML and 2.7 ML) which match those of the QW states.

The QW data was then used to calculate the magnetic coupling. The periods and phases of the magnetic coupling were determined from the QW states, and the relative strength of the long- and short-period couplings was used as a fitting parameter. Comparing this calculation (Fig. 2e) with the experimental data (Fig. 2d) shows that the periods and phases of the magnetic coupling are determined by the momentum-resolved QW states.

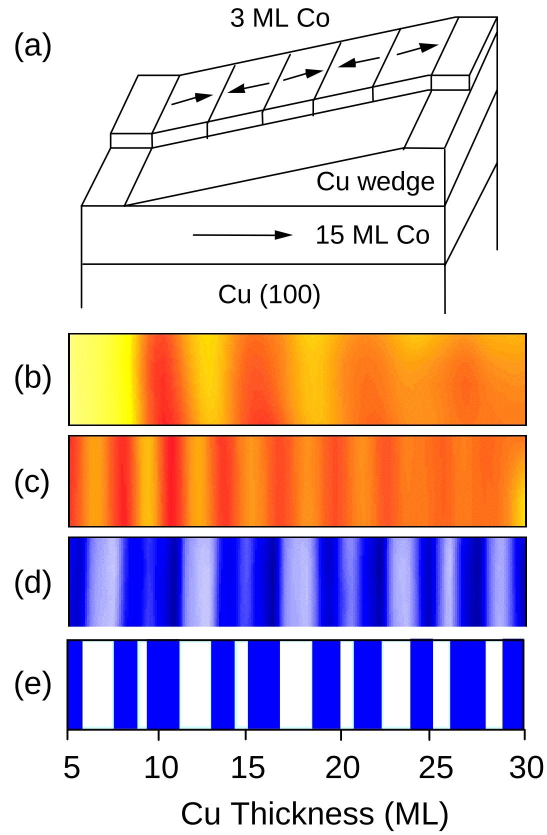

Figure 2. (a) Schematic drawing of sample used to compare the QW states with the oscillatory magnetic coupling. The QW states are measured on the side without the Co cap, and the coupling is measured on the side with the Co cap. (b) Long-period QW states: DOS at the belly of the Fermi surface oscillates with 5.6 ML periodicity of the Cu thickness. (c) Short-period QW states: DOS at the neck of the Fermi surface oscillates with 2.7 ML periodicity of the Cu thickness. (d) Magnetic coupling: Magnetic x-ray linear dichroism of the Co 3p photoemission peak was measured to determine the magnetization direction of the top Co layer. Light (dark) regions correspond to antiferromagnetic (ferromagnetic) coupling. (e) Calculated coupling based on the period and phase information from the QW states at the neck and belly of the Fermi surface. Light (dark) regions correspond to antiferromagnetic (ferromagnetic) coupling.

PROJECT II: SPATIAL VARIATION OF THE QW WAVEFUNCTION

The quantum confined electrons form standing waves with nodes and antinodes of the envelope function, pictured by the red curves in Fig. 1. New methods need to be developed to measure the position of the nodes and antinodes. In this work, we develop one such method that is analogous to measuring the nodes and antinodes of a vibrating guitar string. In the latter case, lightly touching the string near a node will not change the sound. However, lightly touching the string near the antinode will cause the sound to be damped. Thus, by touching different positions along the string, one can map out the spatial variation of the vibrations.

Similar to lightly touching a vibrating string with a finger, the QW electron standing wave in a Cu thin film was "touched" with an atomic layer of Ni. By touching different positions of the standing wave, one can map the wavefunction because the result depends on whether the Ni is at a node or an antinode of the QW envelope function. Figure 3a shows the double-wedge structure used to probe many different positions inside the QW on a single sample. First a Cu wedge is deposited onto a Co(100) substrate, followed by a monolayer of Ni. Then a second Cu wedge with the same slope as the first is deposited along the perpendicular direction. Going from point B to D, the overall Cu film thickness is constant, and the Ni position within the film continuously changes from one side to the other. Going from point A to C, the Ni remains in the center of the Cu film and the overall Cu thickness increases. In this manner, it is possible to independently vary the Ni position and the overall Cu thickness.

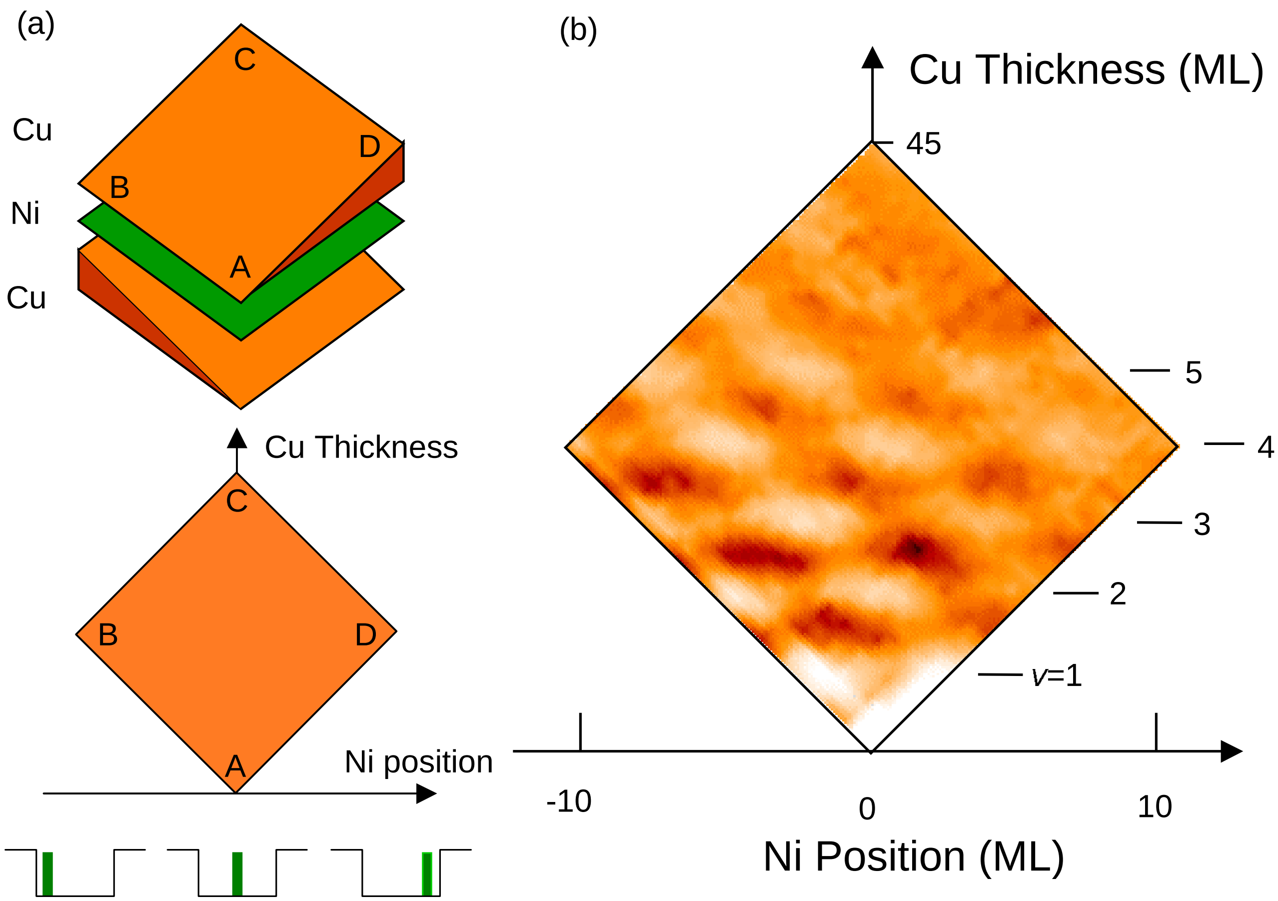

Figure 3. (a) Schematic drawing of the double-wedge sample used to probe the QW wavefunction. This enables independent variation of the overall Cu film thickness and the position of the Ni monolayer. (b) Density of states at the Fermi level using normal photoemission on this double wedge. The oscillations with the Cu thickness are from the QW states, as in Fig. 2b. The new result is the oscillations with the Ni position (horizontal direction), which arise from the Ni monolayer being located at a node or antinode of the QW envelope function.

Figure 3b shows the DOS at the Fermi level for the normal photoemission. The oscillations in the Fermi level DOS as a function of Cu thickness (vertical axis) are due to the formation of QW states at the Fermi level, as in Fig. 2b. Each peak labeled by ν corresponds to a different QW state at the belly of the Fermi surface. Choosing a particular QW state (i.e. fixed Cu thickness), one may then sweep the Ni "touch" layer from one side of the film to the other. The new result is that the DOS oscillates as a function of Ni position (horizontal axis). These oscillations occur because the Ni monolayer will have a different effect depending on whether it is at a node or antinode of the QW envelope function. Qualitatively, the intensity maxima (minima) should correspond to the antinode (node) of the QW envelope function. In this manner, the spatial variation of the QW states has been mapped out for a series of QW states labeled by $\nu = 1,2,3,\ldots$

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